

Tau lepton production and decays: perspective of multi-dimensional distributions and Monte Carlo methods

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Abstract

Status of τ lepton decay Monte Carlo generator **TAUOLA**, its main applications and recent developments are reviewed. It is underlined, that in recent efforts on development of new hadronic currents, the multi-dimensional nature of distributions of the experimental data must be taken with a great care: lesson from comparison and fits to the BaBar and Belle data is recalled. It was found, that as in the past at a time of comparisons with CLEO and ALEPH data, proper fitting, to as detailed as possible representation of the experimental data, is essential for appropriate developments of models of τ decay dynamic.

This multi-dimensional nature of distributions is also important for observables where τ leptons are used to constrain experimental data. In later part of the presentation, use of the **TAUOLA** program for phenomenology of W, Z, H decays at LHC is addressed, in particular in the context of the Higgs boson parity measurements. Some new results, relevant for QED lepton pair emission are mentioned as well.

**Presented on the 14th International Workshop on Tau Lepton Physics
19-23 September, 2016, IHEP, Beijing, China**

1 Introduction

The **TAUOLA** package [1, 2, 3, 4] for simulation of τ -lepton decays and **PHOTOS** [5, 6, 7] for simulation of QED radiative corrections in decays, are computing projects with a rather long history. Written and maintained by well-defined (main) authors, they nonetheless migrated into a wide range of applications where they became ingredients of complicated simulation chains. As a consequence, a large number of different versions are presently in use. Those modifications, especially in case of **TAUOLA**, are valuable from the physics point of view, even though they often did not find the place in the distributed versions of the program. From the algorithmic point of view, versions may differ only in details, but they incorporate many specific results from distinct τ -lepton measurements or phenomenological projects. Such versions were mainly maintained (and will remain so) by the experiments taking precision data on τ leptons. Interesting from the physics point of view changes are still developed in **FORTRAN**. That is why, for convenience of research partners, part of the **TAUOLA** need still to remain in **FORTRAN** for a few forthcoming years.

Our presentation is organized as follows: Section 2 is devoted to the discussion of initialization for **TAUOLA** hadronic currents. This point was already announced in [8] and presented in [9], that is why, we will address only those points which may be important for the future users. In Section 3 we concentrate on **PHOTOS** Monte Carlo for radiative corrections in decays. The new version of the program is 100 % in **C++** and features emissions of light lepton pairs. Section 4 is devoted to applications of **TAUOLA** for hard processes with final state τ leptons. In particular for observable construction and evaluation of its sensitivity. The Neural Network techniques in particular Machine Learning (ML) techniques were found to be useful. In this context we mention **TauSpinner** algorithm, which was found useful for evaluation of observable for Higgs boson parity measurement. We mention other applications or tests; in particular in the domain of algorithm of calculating spin states of τ pairs in events where high p_T jets are present in pp collisions. Summary Section 5, closes the presentation. Because of the limited space of the contribution,

some results will not be presented in the proceedings. They find their place in publications, prepared with co-authors listed in the References. For these works, the present paper may serve as an advertisement.

2 Currents and structure of TAUOLA Monte Carlo

The program structure did not change significantly since the previous τ conference [8]. Nowadays however, the **C++** implementation become dominant for many aspects of the project and that is why, the core part of the algorithm is gradually rewritten to introduce more modular structure and eventually to translate later the whole code into **C++** in quick well controlled steps. The changes introduced so far, are documented in [9]. This is more complicated task than it was for the completed already transformation of **PHOTOS** [10]. Constraints are more complex. Let us stress importance of the three aspects of the work: (i) construction and implementation of hadronic currents for τ decay currents obtained from models (inspired/evaluated from QCD) (ii) presentation of experimental data in a form suitable to fits (iii) preparations of algorithms and definition of distributions useful for fits.

Already two years ago we have prepared two new sets of currents; the first one based mainly on theoretical consideration, the second on an effort of BaBar collaboration. They are ready to be integrated into main distribution tar-balls for **FORTRAN** and **C++** applications, but we are still not sure if sufficient feed back is collected. Weighted event techniques were found useful: for fits, and for evaluation of observables sensitivities to model parameters.

In description of τ decays and up to a precision level of about 0.2% hadronic currents play the dominant role in evaluation of systematic errors. At this precision level, they constitute an important and well defined building block of the τ -lepton decay description. It is used since the first version of **TAUOLA** Monte Carlo generator as well. A multitude of models and parametrizations tuned to experimental data were used. It is at the same time source of the

problems and opportunities that precision of experimental data surpass significantly predictive power of existing models. Confrontation of model's predictions with experimental data with the help of multi-dimensional distribution has to be central for the future project developments. This was pointed already in Ref. [11] and its importance is clear from our recent experience of work on hadronic currents for 3π decay modes. Parametrization of Ref. [12] had to be modified in [13], even though experimental input was enlarged with single one additional 1-dimensional distribution only. Note further comments in [9], explaining potential limitations of such an approach. This is an essential topic which is behind recently changed re-organization of the **TAUOLA** library. Appropriate choices should be coordinated between **TAUOLA** Monte Carlo and fitting programs. Also, it should be possible, that hadronic currents can be coded in other than **FORTRAN** programming language. They have to be easy to modify by experimental user.

That is why, all variables of **TAUOLA** initializations are stored now in **COMMON** blocks, which can be accessed from other programming languages. Version of Ref. [9] evolved from a variant presented on τ conference of 2004 [14] and used by the BaBar collaboration. Program was supplemented with multitude of anomalous τ decay modes as well as with parametrization of our theoretical works of the last decay (of different level of theoretical sophistication depending on decay channel). Details of decay matrix element parametrizations can be easily modified by the user, without the need of recompilation.

3 PHOTOS Monte Carlo for bremsstrahlung: its systematic uncertainties

Over the last two years no major upgrades for functionalities were introduced into PHOTOS Monte Carlo, except introduction of emission of lepton pairs. Documentation of the program [10], was updated and published finally.

Numerical tests for pair emission algorithm are advanced, but remain unpublished as of the time when

the proceedings material had to be submitted.

4 TAUOLA - hard process - TauSpinner algorithm

In the development of packages such as **TAUOLA** or **PHOTOS**, questions of tests and appropriate relations to users' applications are essential for their usefulness. In fact, user applications may be much larger in size and human efforts than the programs discussed here. Good example of such 'user applications' are complete environments to simulate physics process and control detector response at the same time. Distributions of final state particles are not always of direct interest. Often properties of intermediate states (manifesting through spin state of τ -leptons): e.g. coupling constants, masses or parity are of prime interest. As a consequence, it is useful that such intermediate state properties are under direct control of the experimental user and can be manipulated to understand detector responses.

In that perspective, the algorithm of **TauSpinner** [15] to study detector response to spin effects in Z, W and H decays, represents a potentially important development. The program is calculating weights corresponding to changes of the physics assumption. As an input, events stored on the data file are used. There is no need to repeat simulations of the detector response whenever physics process is changed. The program has undergone several refinements [16, 17], and recently [18] where spin weight calculation taking into account matrix elements with two additional jets was introduced. This work, provided technical framework for improvements in calculation of spin effects of Drell-Yan τ -lepton pair production process. It is straightforward to extend results of [19, 20] to the case when spin effects are taken into account. Note, that electroweak corrections can be used in calculation of complete spin correlations in Z/γ^* mediated processes.

With the help of **TauSpinner** we could evaluate observable to study Higgs parity, in its cascade decay with intermediate τ leptons [21]. More precisely; we have investigated the potential for measur-

ing the CP state of the Higgs boson in $H \rightarrow \tau\tau$ decay, with consecutive τ -lepton decays in the channels: $\tau^\pm \rightarrow \rho^\pm \nu_\tau$ and $\tau^\pm \rightarrow a_1^\pm \nu_\tau$ combined. Subsequent decays $\rho^\pm \rightarrow \pi^\pm \pi^0$, $a_1^\pm \rightarrow \rho^0 \pi^\pm$ and $\rho^0 \rightarrow \pi^+ \pi^-$ were taken into account. We have extended method of Ref. [22], where the acoplanarity angle for the planes build on the visible decay products $\pi^\pm \pi^0$ of $\tau^\pm \rightarrow \pi^\pm \pi^0 \nu_\tau$, were used. The angle is sensitive to transverse spin correlations, thus to parity.

Also in the case of the cascade decays of $\tau \rightarrow a_1 \nu$, information on the CP state of Higgs can be extracted from the acoplanarity angles. In the cascade decay $a_1^\pm \rightarrow \rho^0 \pi^\pm$, $\rho^0 \rightarrow \pi^+ \pi^-$ up to four planes can be defined, thus 16 distinct acoplanarity angle distributions are available for $H \rightarrow \tau\tau \rightarrow a_1^+ a_1^- \nu\nu$. The distributions carry supplementary but correlated information. It is cumbersome to evaluate an overall sensitivity.

We have investigated the sensitivity potential of such analysis, by developing and applying ML techniques. We quantified possible improvements when multi-dimensional phase-space of outgoing decay products directions is used, instead of one-dimensional projections i.e. the acoplanarity angles.

We have not taken into account ambiguities resulting from detector uncertainties or background contamination. We have concentrated on the usefulness of ML methods and $\tau \rightarrow 3\pi\nu$ decays for Higgs boson parity measurement. Let us quote an example of numerical result taken from Ref. [21] and recall the table 1.

5 Summary and future possibilities

Versions of the hadronic currents available for the TAUOLA library until recently, were often based on old models and experimental data of 90's. An alternative implementation of currents, based on the Resonance Chiral Lagrangian, or other approaches is prepared and tested for the decay channels to 2, 3, 4 and 5 pions but it was not confronted with the experimental distributions of multi dimensional nature. Also collecting feed back from community of users may

not have been completed. Parametrizations used for the default simulations in BaBar collaboration is now available. Further advantage of this new option is a multitude of rare and anomalous τ decay channels. In fact, such options were extended even further. With the help of C++ interface, user provided hadronic current(s) or decay matrix element(s), can be used to replace the ones of the library, at any moment of program execution.

Methods for confrontation of program predictions with the experimental data are not developing fast. Solutions postulated already in [11] are still not used in full. We rely on comparison of results with one-dimensional histograms of invariant masses formed from sub-groups of τ decay products. They have to be defined for each decay channel separately and unfolded from the experimental backgrounds.

The status of associated projects: TAUOLA universal interface and TauSpinner was reviewed. Also new results for the high-precision version of PHOTOS for QED radiative corrections in decays, were mentioned. All programs are ready for C++ applications thanks to the HepMC interfaces.

Presentation of the TAUOLA general-purpose C++ interface was given and its applications were shown. An algorithm for study, with the help of weights calculated from kinematic of events stored on data files, detector responses to spin effects and production process variants in Z , W and H decays was shown. The corresponding program TauSpinner, is useful, e.g. to study Higgs parity sensitive observables at LHC. In this case, efficiency of multi-dimensional distributions to constrain Higgs parity in cascade decays starting from $H \rightarrow \tau^+ \tau^-$, $\tau^\pm \rightarrow \nu_\tau a_1^\pm$, was demonstrated.

Acknowledgements

The work on TAUOLA would not be possible without continuous help and encouragements from experimental colleagues. The work of all co-authors of the papers devoted to TAUOLA development was of great importance. I hope, that it is clearly visible from my contribution. This research was supported in part by the Research Executive Agency (REA) of the European Union under the Grant Agreement PITN-GA-2012-316704 (HiggsTools) and by funds of Polish National Science Centre under decision UMO-2014/15/ST2/00049.

| Features/variables | Decay mode: $\rho^\pm - \rho^\mp$ $\rho^\pm \rightarrow \pi^0 \pi^\pm$ | Decay mode: $a_1^\pm - \rho^\mp$ $a_1^\pm \rightarrow \rho^0 \pi^\mp, \rho^0 \rightarrow \pi^+ \pi^-$ $\rho^\mp \rightarrow \pi^0 \pi^\mp$ | Decay mode: $a_1^\pm - a_1^\mp$ $a_1^\pm \rightarrow \rho^0 \pi^\pm, \rho^0 \rightarrow \pi^+ \pi^-$ |
|------------------------------------------------------------|---------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|
| True classification | 0.782 | 0.782 | 0.782 |
| $\varphi_{i,k}^*$ | 0.500 | 0.500 | 0.500 |
| $\varphi_{i,k}^*$ and y_i, y_k | 0.624 | 0.569 | 0.536 |
| 4-vectors | 0.638 | 0.590 | 0.557 |
| $\varphi_{i,k}^*$, 4-vectors | 0.638 | 0.594 | 0.573 |
| $\varphi_{i,k}^*$, y_i, y_k and m_i^2, m_k^2 | 0.626 | 0.578 | 0.548 |
| $\varphi_{i,k}^*$, y_i, y_k, m_i^2, m_k^2 and 4-vectors | 0.639 | 0.596 | 0.573 |

Table 1: Average probability p_i (calculated as explained in Ref. [21]) that a model predicts correctly event x_i to be of a type A (scalar), with training being performed for separation between type A and B (pseudo-scalar).

References

- [1] S. Jadach, J. H. Kühn, Z. Was, Tauola: A library of monte carlo programs to simulate decays of polarized tau leptons, Comput. Phys. Commun. 64 (1990) 275.
- [2] M. Jezabek, Z. Was, S. Jadach, J. H. Kühn, The tau decay library tauola, update with exact o(alpha) qed corrections in tau \rightarrow mu. (e) neutrino anti-neutrino decay modes, Comput. Phys. Commun. 70 (1992) 69.
- [3] S. Jadach, Z. Was, R. Decker, J. H. Kühn, The tau decay library tauola: Version 2.4, Comput. Phys. Commun. 76 (1993) 361.
- [4] P. Golonka, et al., The tauola-photos-F environment for the TAUOLA and PHOTOS packages, release II, Comput. Phys. Commun. 174 (2006) 818–835. [arXiv:hep-ph/0312240](#), [doi:10.1016/j.cpc.2005.12.018](#).
- [5] E. Barberio, B. van Eijk, Z. Was, Photos: A universal monte carlo for qed radiative corrections in decays, Comput. Phys. Commun. 66 (1991) 115.
- [6] E. Barberio, Z. Was, Photos: A universal monte carlo for qed radiative corrections. version 2.0, Comput. Phys. Commun. 79 (1994) 291–308.
- [7] P. Golonka, Z. Was, PHOTOS Monte Carlo: A precision tool for QED corrections in Z and W decays, Eur. Phys. J. C45 (2006) 97–107. [arXiv:hep-ph/0506026](#).
- [8] Z. Was, The τ leptons theory and experimental data: Monte Carlo, fits, software and systematic errors, Nucl. Part. Phys. Proc. 260 (2015) 47–51. [arXiv:1412.2937](#), [doi:10.1016/j.nuclphysbps.2015.02.010](#).
- [9] M. Chrzaszcz, T. Przedzinski, Z. Was, J. Zaremba, TAUOLA of tau lepton decays—framework for hadronic currents, matrix elements and anomalous decays [arXiv:1609.04617](#).
- [10] N. Davidson, T. Przedzinski, Z. Was, PHOTOS Interface in C++: Technical and Physics Documentation, Comput. Phys. Commun. 199 (2016) 86–101. [arXiv:1011.0937](#), [doi:10.1016/j.cpc.2015.09.013](#).
- [11] D. Asner, et al., Hadronic structure in the decay $\tau^- \rightarrow \tau_\nu \pi^- \pi^0 \pi^0$ and the sign of the τ_ν helicity, Phys.Rev. D61 (2000) 012002. [arXiv:hep-ex/9902022](#), [doi:10.1103/PhysRevD.61.012002](#).
- [12] O. Shekhovtsova, T. Przedzinski, P. Roig, Z. Was, Resonance chiral Lagrangian currents and τ decay Monte Carlo, Phys.Rev.

- D86 (2012) 113008. [arXiv:1203.3955](#),
doi:10.1103/PhysRevD.86.113008.
- [13] I. Nugent, T. Przedzinski, P. Roig, O. Shekhovtsova, Z. Was, Resonance chiral Lagrangian currents and experimental data for $\tau^- \rightarrow \pi^- \pi^- \pi^+ \nu_\tau$, Phys.Rev. D88 (9) (2013) 093012. [arXiv:1310.1053](#), doi:10.1103/PhysRevD.88.093012.
- [14] Z. Was, P. Golonka, TAUOLA as tau Monte Carlo for future applications, Nucl. Phys. Proc. Suppl. 144 (2005) 88–94. [arXiv:hep-ph/0411377](#), doi:10.1016/j.nuclphysbps.2005.02.012.
- [15] Z. Czyzula, T. Przedzinski, Z. Was, TauSpinner Program for Studies on Spin Effect in tau Production at the LHC, Eur.Phys.J. C72 (2012) 1988. [arXiv:1201.0117](#), doi:10.1140/epjc/s10052-012-1988-z.
- [16] S. Banerjee, J. Kalinowski, W. Kotlarski, T. Przedzinski, Z. Was, Ascertaining the spin for new resonances decaying into tau+ tau- at Hadron Colliders, Eur.Phys.J. C73 (2013) 2313. [arXiv:1212.2873](#), doi:10.1140/epjc/s10052-013-2313-1.
- [17] T. Przedzinski, E. Richter-Was, Z. Was, TauSpinner: a tool for simulating CP effects in $H \rightarrow \tau\tau$ decays at LHC, Eur. Phys. J. C74 (11) (2014) 3177. [arXiv:1406.1647](#), doi:10.1140/epjc/s10052-014-3177-8.
- [18] J. Kalinowski, W. Kotlarski, E. Richter-Was, Z. Was, Production of τ lepton pairs with high p_T jets at the LHC and the TauSpinner reweighting algorithm, Eur. Phys. J. C76 (10) (2016) 540. [arXiv:1604.00964](#), doi:10.1140/epjc/s10052-016-4361-9.
- [19] E. Richter-Was, Z. Was, Separating electroweak and strong interactions in DrellYan processes at LHC: leptons angular distributions and reference frames, Eur. Phys. J. C76 (8) (2016) 473.
- [20] E. Richter-Was, Z. Was, W production at LHC: lepton angular distributions and reference frames for probing hard QCD [arXiv:1609.02536](#).
- [21] R. Józefowicz, E. Richter-Was, Z. Was, Potential for optimizing the Higgs boson CP measurement in $H \rightarrow \tau\tau$ decays at the LHC including machine learning techniques, Phys. Rev. D94 (9) (2016) 093001.
- [22] G. Bower, T. Pierzchala, Z. Was, M. Worek, Measuring the Higgs boson's parity using $\tau \rightarrow \rho\nu$, Phys.Lett. B543 (2002) 227–234.